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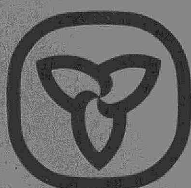
Research report W48

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NUTRIENT ENRICHMENT STUDIES IN A MARL LAKE

Lake-on-the-mountain,
Prince Edward County

January, 1974



Ontario

Ministry
of the
Environment

The Honourable
William G. Newman,
Minister

Everett Biggs,
Deputy Minister

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NUTRIENT ENRICHMENT STUDIES IN A MARL LAKE:
LAKE-ON-THE-MOUNTAIN, PRINCE EDWARD COUNTY

by
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January, 1974
Research Report W48

Research Branch
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ABSTRACT

From limnological studies in 1967 and 1970, Lake-on-the-Mountain was found to represent a mesotrophic, marl lake which in summer develops pronounced thermal stratification and an anaerobic hypolimnion. Laboratory and field studies suggest that phytoplankton development is restricted due to a low availability of nitrogen and phosphorus otherwise the lake is quite fertile. Large beds of macrophytic flora in the littoral zone would appear to influence to some degree the availability of these two nutrients for phytoplankton growth.

Addition of organic carbon, as glucose, with or without the inclusion of nitrogen plus phosphorus, was not found to stimulate phytoplankton growth during in situ fertilization trials.

On the basis of phytoplankton responses obtained in isolated epilimnetic waters enriched with nitrogen plus phosphorus, it is recommended that nutrient laden inputs to a receiving water, which is capable of diluting such loadings one thousand fold, should be limited to not more than 0.4 mg/l total phosphorus and 6.4 mg/l available nitrogen, and more ideally to about one-half of these values to prevent the fertility of the receiving water from increasing to a eutrophic level.

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INTRODUCTION

Guidelines governing the entry of nutrients as pollution to Ontario surface waters are necessary to prevent excessive developments of algae and a concomitant deterioration of water quality.

Since 1967 a research program to clarify relationships between phytoplankton development and nutrient availability has been in progress with particular emphasis focused on those substances amenable to control - organic carbon (BOD), nitrogen, phosphorus. Phase I of the study involved characterization of these relationships based on samples obtained from eight lakes which lie within the Trent River Drainage Basin and represent a variety of trophic situations. At least one variable, inorganic carbon (alkalinity) appeared to be a background yet significant factor in determining algal responses (Christie, 1968; 1969). Phase II of the program focused on phytoplankton-nutrient relationships in the Bay of Quinte, one of the most fertile bodies of water in the Province, but where the above parameter, alkalinity, is essentially constant (McCombie, 1967; Christie, 1973; Hurley, 1970).

Qualification of tentative relationships between nutrient availability and phytoplankton development obtained from the preceding were then to be more

critically assessed by means of in situ controlled fertilization experiments to be carried out in natural, relatively unproductive environs.

The alkalinity of the larger bodies of Ontario surface waters tend to lie somewhere within the range of 6 - 120 mg/l as CaCO_3 . Kushog, an oligotrophic precambrian lake provided the location for enrichment studies at the low end of the alkalinity scale (Christie, in prep.). Lake-on-the-Mountain, when examined in 1967, was found to display a general water chemistry comparable to the nearby fertile Bay of Quinte, but not excessive growths of phytoplankton. This lake therefore appeared to offer an ideal site for controlled fertilization experiments at the upper end of the alkalinity range.

The results of these experiments which were carried out in 1970, and a description of lake limnology as observed in 1967 and 1970, are provided in the following report.

STUDY AREA

Lake-on-the-Mountain is located in North Marysburgh Township, Prince Edward County at a longitude of $77^{\circ} 03'$ and a latitude of $44^{\circ} 02'$ (Figure 1, 2). The lake, situated on a limestone escarpment 52 metres above the Bay of Quinte, has an area of 81 hectares with a

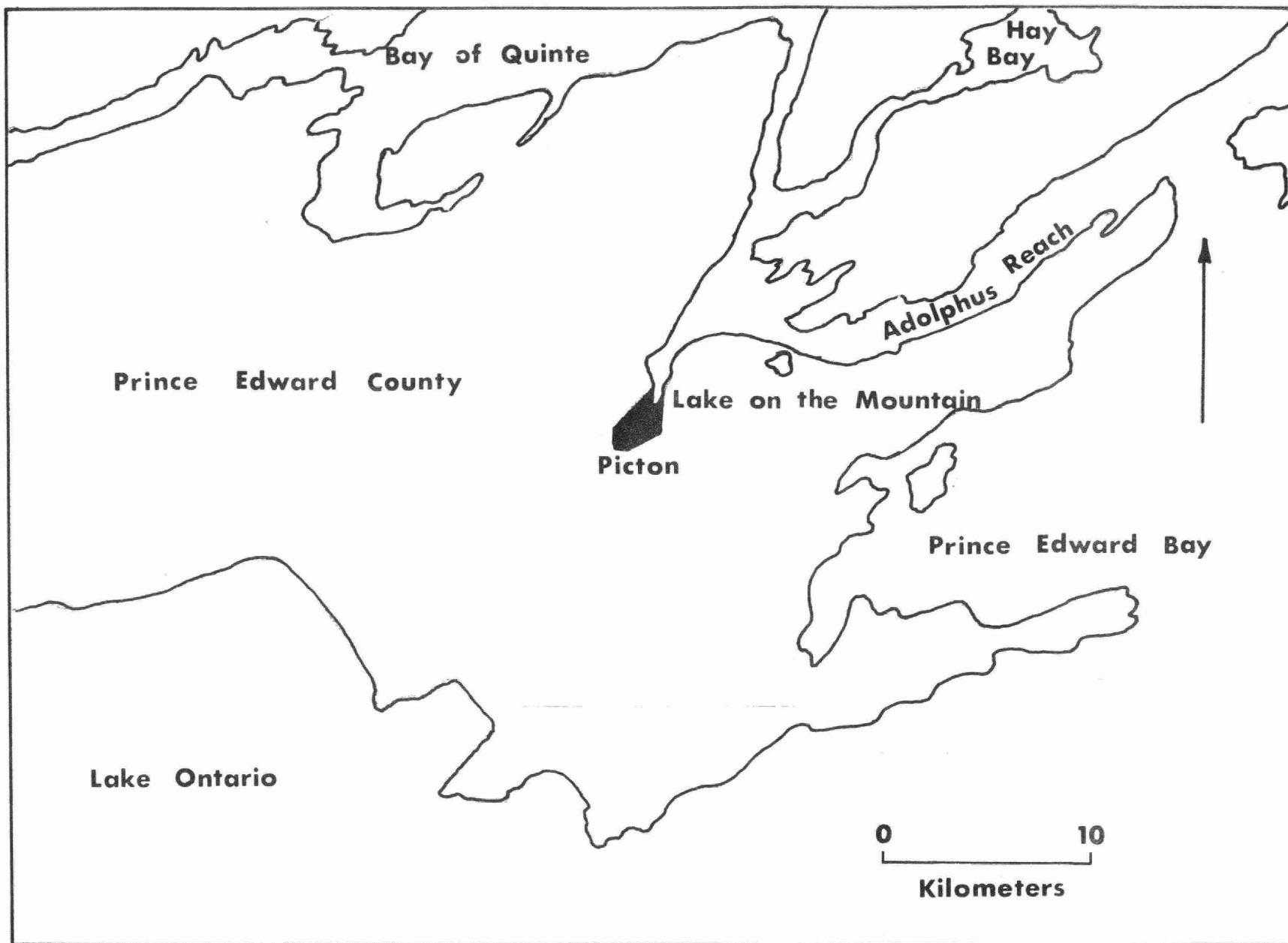


Figure 1

Partial Map of Prince Edward County, Ontario,
showing location of Lake-on-the-Mountain.

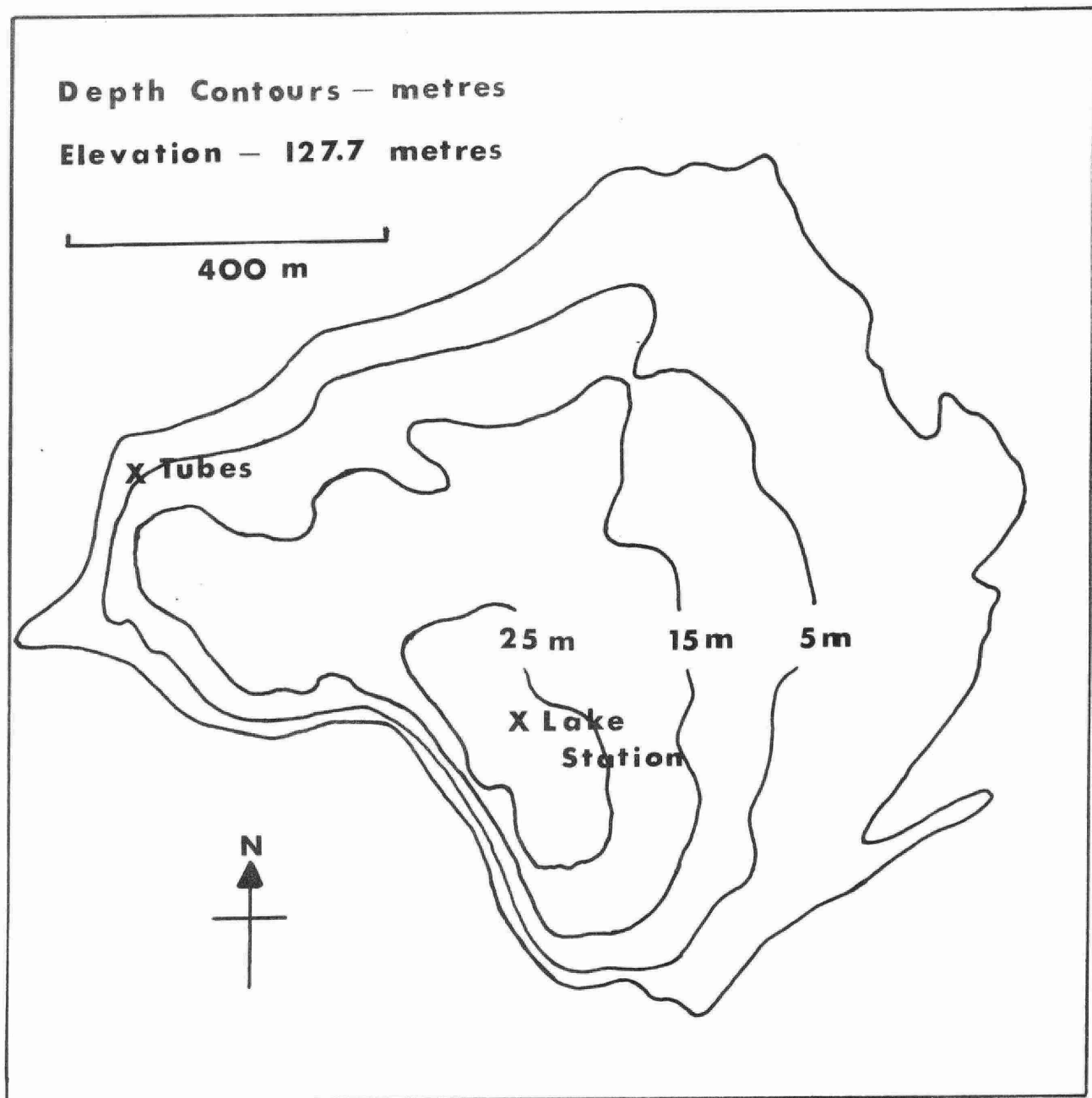


Figure 2

Map of Lake-on-the-Mountain showing depth contours at 5,15 and 25 metres and the location of the lake sampling station and site of field enrichment experiments.

maximum depth of 30 metres and an average depth of about 10 metres. At the deepest point the bottom is covered with almost 7 metres of gyttja, silt and clay over a limestone bedrock (Terasmae and Miryneck, 1964). The lake volume is about 10.4×10^6 cubic metres and in mid-summer when sharp stratification occurs the hypolimnion makes up about 42 percent of this volume (MacLeod, unpublished).

Lake-on-the-Mountain has a drainage area of 3,108 hectares of which 121 hectares is woody swamp. Surface runoff in the spring plus influxes of groundwater below the lake surface during the summer are considered to be responsible for maintaining the lake level which varies no more than about 3/4 metres between April and October. A limited outflow of water occurs via a natural channel at the northeast corner of the lake. The major water outlets are two pipes, total capacity 3.45 cubic metres per minute, which supply water to the Glenora Fisheries Research Station, Ministry of Natural Resources, located below the bluff.

The lake is rock rimmed for the most part, a 23 metre bluff along the southwestern shore providing protection from prevailing winds. On the northeastern shore, where several cottages, a motel and a park are located, a retaining wall was constructed many years ago which resulted in the level of the lake being raised approximately 3 metres.

The location of the fertilization experiments (Tubes) and the sampling location to examine the characteristics of the lake are indicated.

METHODS AND MATERIALS

Sampling

Composite sampling of the trophogenic zone of the lake at two week intervals from mid-May to November, 1967 and 1970, was accomplished by passing a narrow mouth one litre bottle, mounted in a weighted harness, through a column of water double the depth of water transparency as determined using a secchi disc. The depth of the one percent isophot was established occasionally in 1967 using a GM submarine photometer. Stratified sampling of the water column was carried out three times in 1967 and monthly in 1970 usually at three metre intervals to a maximum depth of 15 metres using a four litre opaque Van Dorn bottle.

Analyses

Measurements of water temperature and oxygen content to a depth of 15 metres, at one metre intervals, were obtained bimonthly in 1970 and less frequently in 1967 using primarily a YSI combination temperature oxygen probe apparatus. Additional data were obtained from

personnel of the Fisheries Research Station. Various chemical analyses were carried out on unfiltered water samples. Filtered water for chemical determinations was prepared by passing a 500 ml aliquot of raw water through a glass fibre filter which had been prerinsed with two 25 ml washings of the sample to be filtered. Chlorophyll a estimates were based on the residue from a 500 ml sample, treated with 1 ml saturated MgCO_3 , retained when the sample was filtered through a 47 mm 1.2 micron membrane. The above analyses were carried out at the Toronto laboratory of the Ministry of the Environment according to methods described by Brydges (1970). The carbon, nitrogen and phosphorus contents of the seston were based on analyses of concentrates which were also used for phytoplankton enumeration.

Phytoplankton

Phytoplankton standing crops were sampled at the same time and depth as the above and one litre samples were preserved with HgCl in 1967 and Lugol's solution in 1970. Procedures for the concentration and enumeration of phytoplankton have been described elsewhere (Christie, 1973). Plankton production measurements were carried out three times in 1967 and at monthly intervals in 1970 using the ^{14}C as described in Johnson et al (1968) with two light bottles and one dark bottle at each depth. Four hour exposure periods began two hours before mid-day.

The radioactivity of the samples was determined using a Tri-Carb scintillation spectrometer and the counts were quench corrected. The data are based only on the radioactivity associated with the algae.

Laboratory enrichment experiments were carried out in an environmental chamber using 300 ml aliquots of raw water contained in 500 ml screw capped flasks that were agitated on a slowly moving shaker table. Light intensity from a mixture of fluorescent and incandescent lamps was 40000 lux at table level and the temperature was maintained at $20^{\circ} \pm 2^{\circ}$ C. The cultures were exposed to a 14:10 hour light/dark cycle. Nitrogen and phosphorus were added as KNO_3 and KH_2PO_4 .

Fertilization experiments in the lake were carried out using enclosures constructed from new, clear polyethylene tubing having a circumference of 1 metre and a wall thickness of 0.10 mm. The upper end of each tube and the lower end of each column (as opposed to bag) were held open by clamping the tubing between two bands of galvanized metal in such a way that the metal was outside the enclosure. The lower end of the columns were wedged into the bottom muds whereas the lower end of the bags were sealed. The enclosures were suspended from a securely anchored framework. The volume and type of enclosure employed in the three field experiments are as follows:

Series I	column	190 litres
Series II	bag	165 litres
Series III	bag	150 litres

Volume differences between Series I, II and III reflect to some degree changes in lake level.

All chemicals were dissolved in glass distilled water before being added to the enclosures at the beginning of each experiment. Sampling to determine changes occurring after fertilization were obtained at weekly intervals from a depth of 0.5 metres in each enclosure and from adjacent lake water. Nutrient enrichment treatments of Series I, II and III are listed in Table I. Chronologically the Series I experiment began in early July, Series II in August, and Series III in September. All experiments were conducted for a period of four weeks.

TABLE I

Nutrient Enrichment Treatments for Series I, II, III

µg/l at time zero

Control (N ₀ P ₀)	NaNO ₃ as N	KH ₂ PO ₄ as P	Glucose as C
Control (N ₀ P ₀)	-	-	-
P ₁	-	24	-
P ₂	-	66	-
N ₁	238	-	-
N ₁ P ₁	238	24	-
N ₁ P ₂	238	66	-
N ₂	896	-	-
N ₂ P ₁	896	24	-
N ₂ P ₂	896	66	-
C	-	-	3250
CN ₁ P ₁	238	24	3250

RESULTS

LAKE LIMNOLOGY

Physical and Chemical Characteristics

Secchi disc estimates of water clarity and seasonal depth changes of water temperature are illustrated in Figure 3. Transparency in 1967 ranged from 3.5 to 7.0 metres and in 1970 from 2.7 to 6.0 metres. A comparison of the mean values of each year of 5.7 and 4.7 metres respectively indicates a reduction in clarity of about 18 percent in three years.

Temperature data for each year, presented on the basis of 5° C isotherm intervals, show the epilimnion to typically penetrate to maximum depth of about 8 metres by late summer, and the presence of a sharply defined metalimnion which eventually descended to a depth of about 10 metres.

Dissolved oxygen concentrations in 1970 (Figure 4) were almost homogeneous with depth in early May but by late July much of the lake volume below a depth of 15 metres was approaching an anaerobic condition. At the same time an instance of supersaturation was observed at a depth of 12 metres in late August.

The mean, minimum and maximum values for various chemical parameters based on both composite sampling of the trophogenic zone and stratified sampling

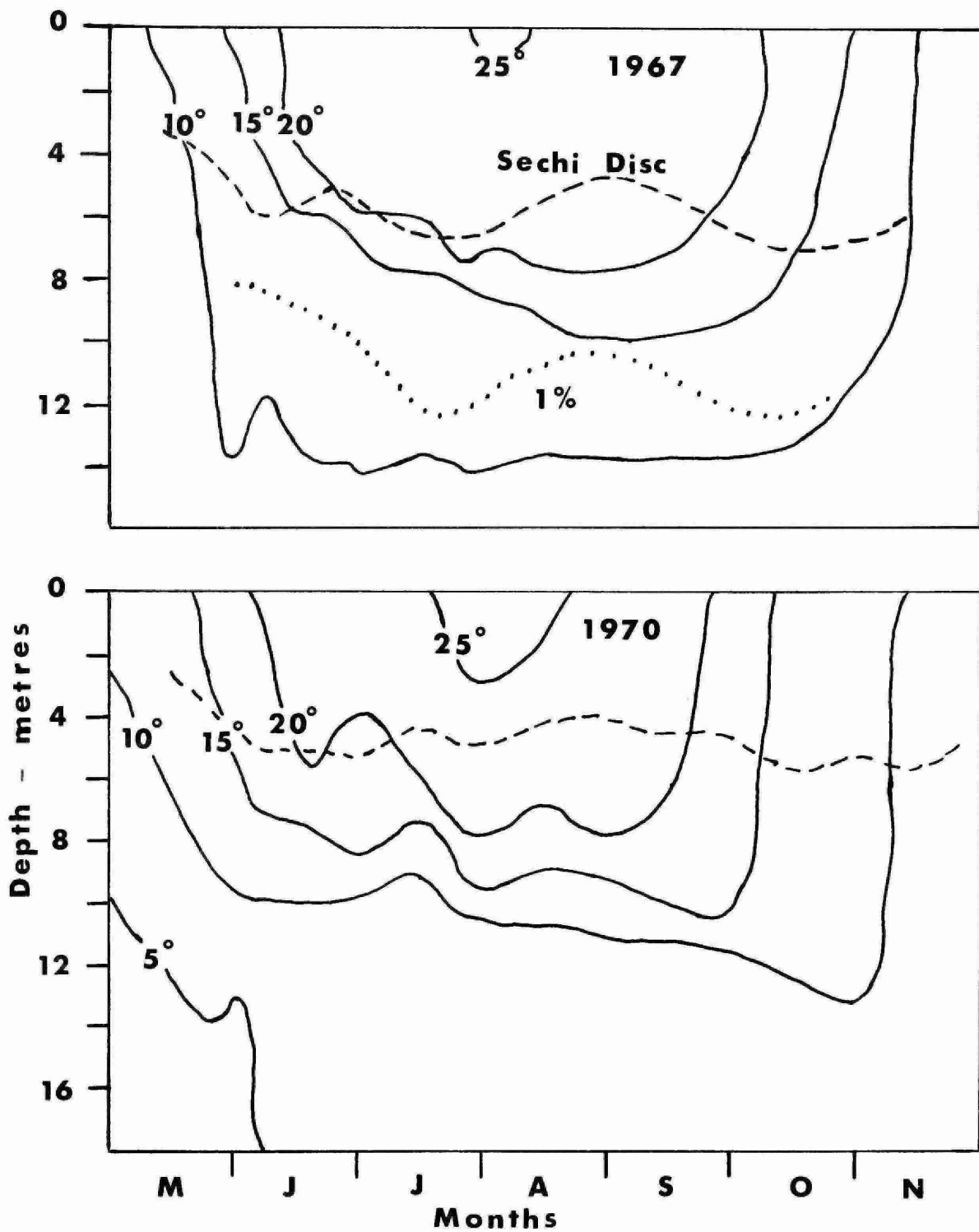


Figure 3

Seasonal depth variations in water temperature (5° C isotherms), secchi disc estimates of water transparency (metres), 1967, 1970, and depth of 1% isophot in 1967.

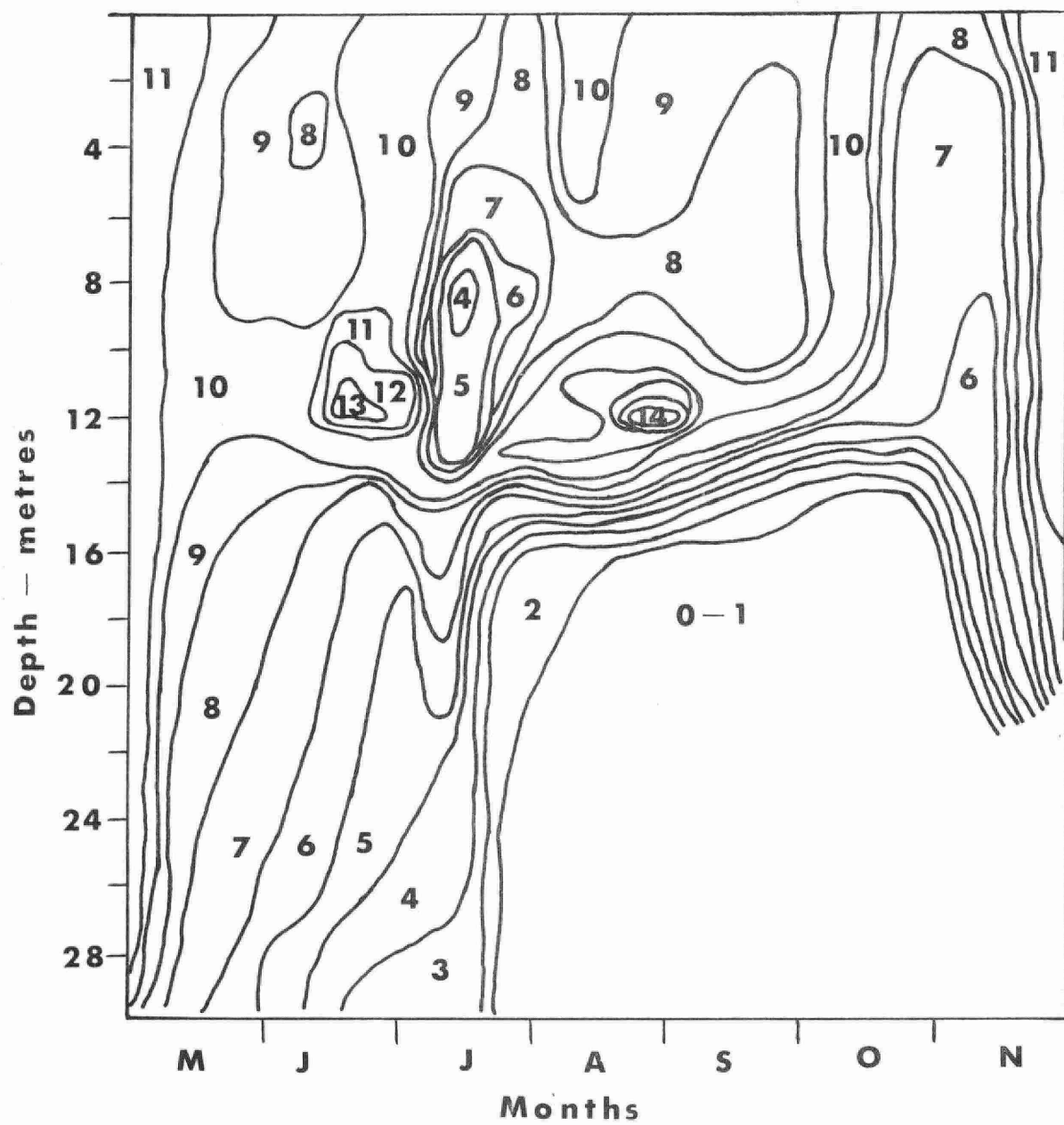


Figure 4
Seasonal depth variations of dissolved oxygen
(mg/l) in 1970.

to a depth of 15 metres are listed in Table III. The relative distribution of carbon, nitrogen, phosphorus and dissolved silicate during the sampling period of 1970 to a depth of 15 metres is indicated in Figures 5, 6, 7.

Phytoplankton

Standing crops of phytoplankton (mm^3/l) and chlorophyll a ($\mu\text{g}/\text{l}$) obtained from composite sampling of the trophogenic zone in 1967 and 1970 are illustrated in Figure 8. Associated changes in total and soluble reactive phosphorus, inorganic nitrogen ($\text{NH}_3 + \text{NO}_3^- + \text{NO}_2^-$), and inorganic carbon are also included. Phytoplankton quantities for the most part ranged from less than $1 \text{ mm}^3/\text{l}$ to slightly more than $3 \text{ mm}^3/\text{l}$, the largest concentration of nearly $5 \text{ mm}^3/\text{l}$ being obtained in August 1967. The highest chlorophyll a level, in excess of $5 \mu\text{g}/\text{l}$, was recorded in 1970.

Inorganic nitrogen concentrations became very low during July and August each year, $10 \mu\text{g}/\text{l}$ or less, and soluble reactive phosphorus undetectable by August in 1967, and for most of the study period in 1970. Inorganic carbon concentrations also showed a decrease from early spring to midsummer from $25 \text{ mg}/\text{l}$ to about $17 \text{ mg}/\text{l}$.

The relative composition of the phytoplankton population, based on this type of sampling (Figure 9), shows a rapid displacement of the Bacillariophyta in May and June by the Cyanophyta with an increasing diversity

TABLE II

Water Chemistry: Lake-on-the-Mountain

Parameter		1967			1970		
		Composite			Composite		
		mean	range	obs.	mean	range	obs.
Calcium	mg/l	39	37-41	2	42	38-48	15
Magnesium	mg/l	3	3-4	2	2	1-6	15
Sodium	mg/l	1	1	2	1	1	15
Potassium	mg/l	1.1	1.1-1.2	2	1.3	1.1-1.6	15
Total Iron	mg/l	0.07	0.05-0.10	2	0.05	0.05-0.12	15
Sulphate	mg/l	26	24-27	2	17	13-24	15
Chloride	mg/l	3	3	2	3	2-3	15
Alkalinity as mg/l CaCO ₃		95	73-108	10	97	88-108	15
Dissolved Solids	mg/l	144	106-180	10	158	127-190	15
Conductivity	mho/cm ³	244	208-247	4	232	209-262	15
pH		8.1	7.6-8.4	10	8.1	7.9-8.5	10
Phosphorus							
Total	µg/l	17	3-40	10	17	9-24	15
Sol. React.	µg/l	3	0-9	10	3	0-1	15
Nitrogen							
Total	µg/l	700	550-1090	10	454	328-527	15
Ammonia	µg/l	11	20-360	10	30	10-70	15
Nitrate	µg/l	6	<10-200	10	<10	<10-30	15
Nitrite	µg/l	1	0-10	10	4	2-10	15
Diss. SiO ₂	mg/l	-	-	-	1.55	0.58-2.85	15

continued.....

TABLE II (continued)

Parameter		1970		
		Profiles		
		mean	range	obs.
Calcium	mg/l	44	35-52	41
Magnesium	mg/l	3	1-9	41
Sodium	mg/l	1	1-2	41
Potassium	mg/l	1.3	0.9-1.6	41
Total Iron	mg/l	0.05	0.05-0.15	41
Sulphate	mg/l	18	13-29	41
Chloride	mg/l	3	2-4	41
Alkalinity as mg/l CaCO_3		100	75-123	41
Dissolved Solids	mg/l	154	125-200	41
Conductivity	mho/cm ³	219	195-282	41
pH		8.2	7.5-8.7	41
Phosphorus				
Total	µg/l	17	6-56	41
Sol. React.	µg/l	3	1-11	41
Nitrogen				
Total	µg/l	590	440-960	41
Ammonia	µg/l	60	10-200	41
Nitrate	µg/l	50	<10-80	41
Nitrite	µg/l	3	1-8	41
Diss. SiO_2	mg/l	1.60	0.28-3.20	41

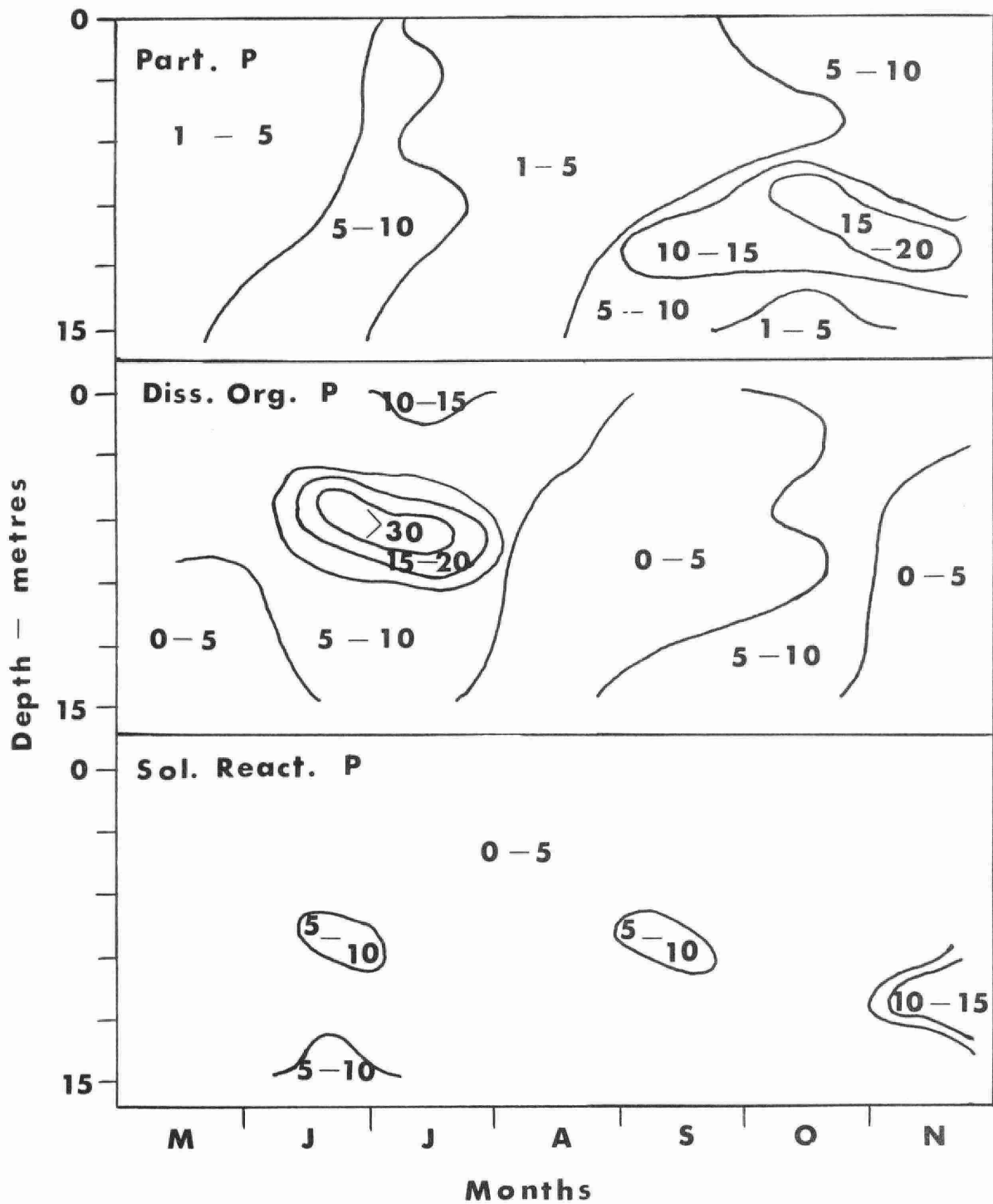


Figure 5

Seasonal depth variations in 1970 of particulate, dissolved organic, and soluble reactive phosphorus ($\mu\text{g P/l}$).

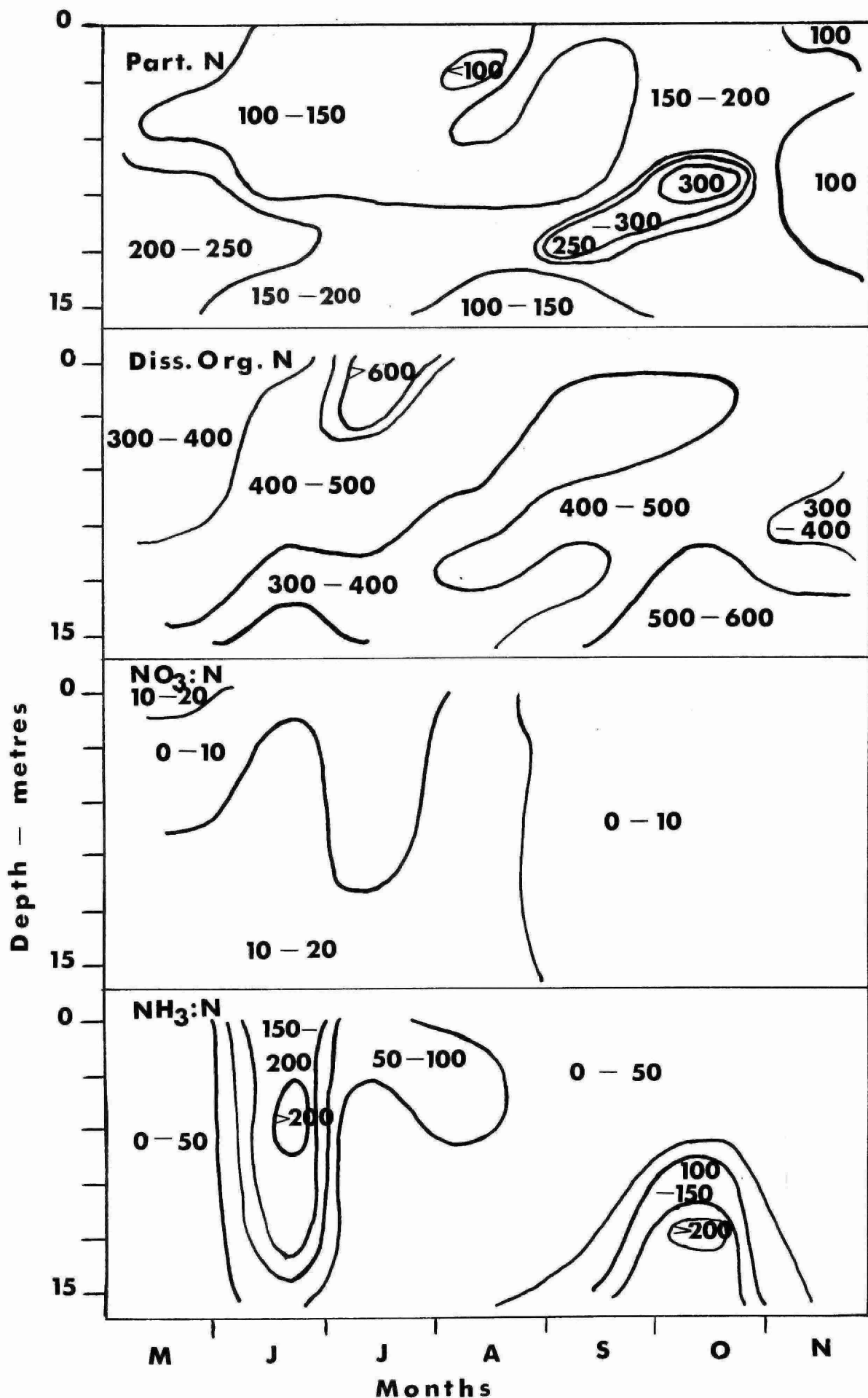


Figure 6

Seasonal depth variations in 1970 of particulate nitrogen, dissolved organic nitrogen, nitrate, and ammonia ($\mu\text{g N/l}$).

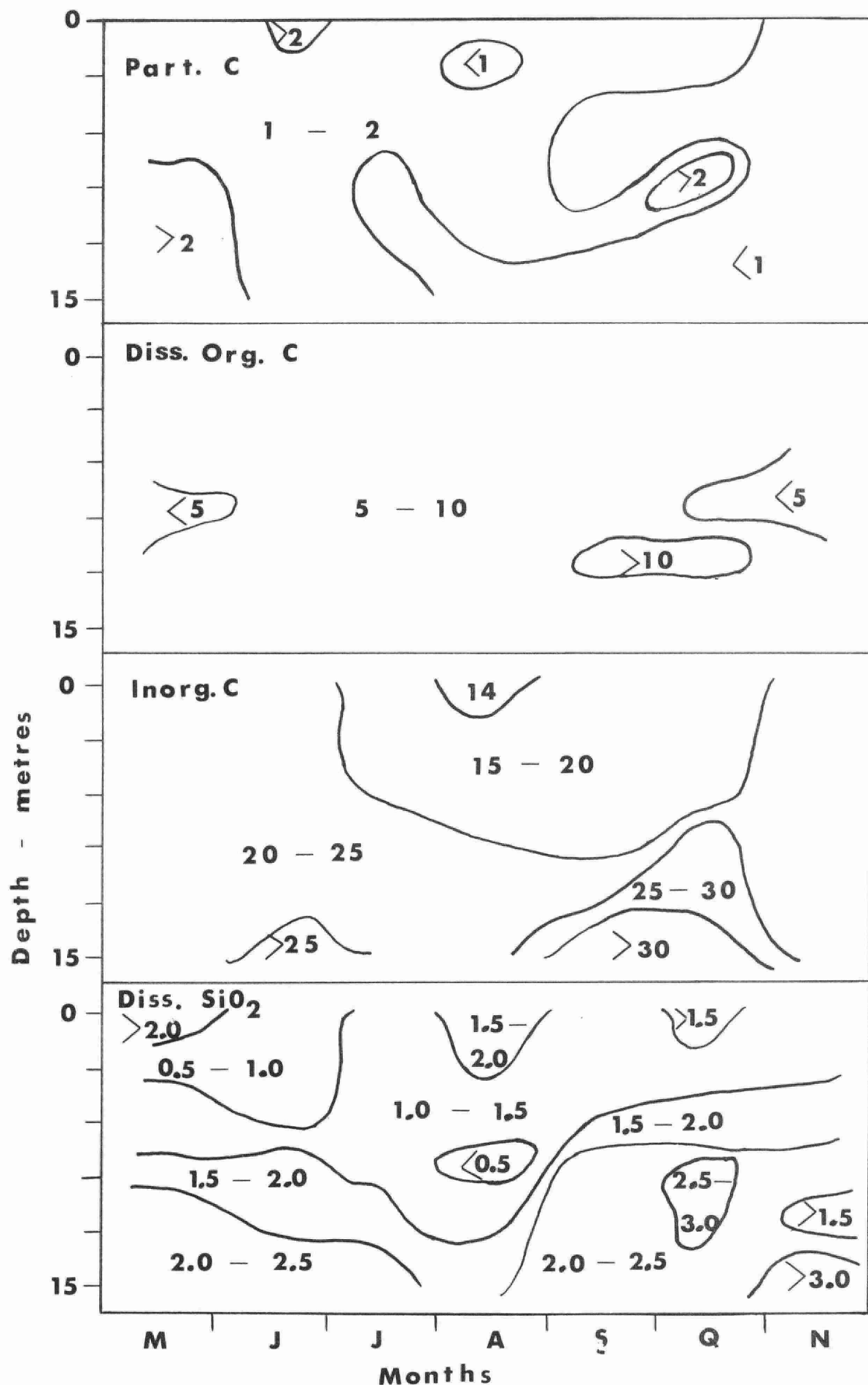


Figure 7

Seasonal depth variations in 1970 of particulate carbon, dissolved organic carbon, inorganic carbon, and dissolved silicate (mg/l).

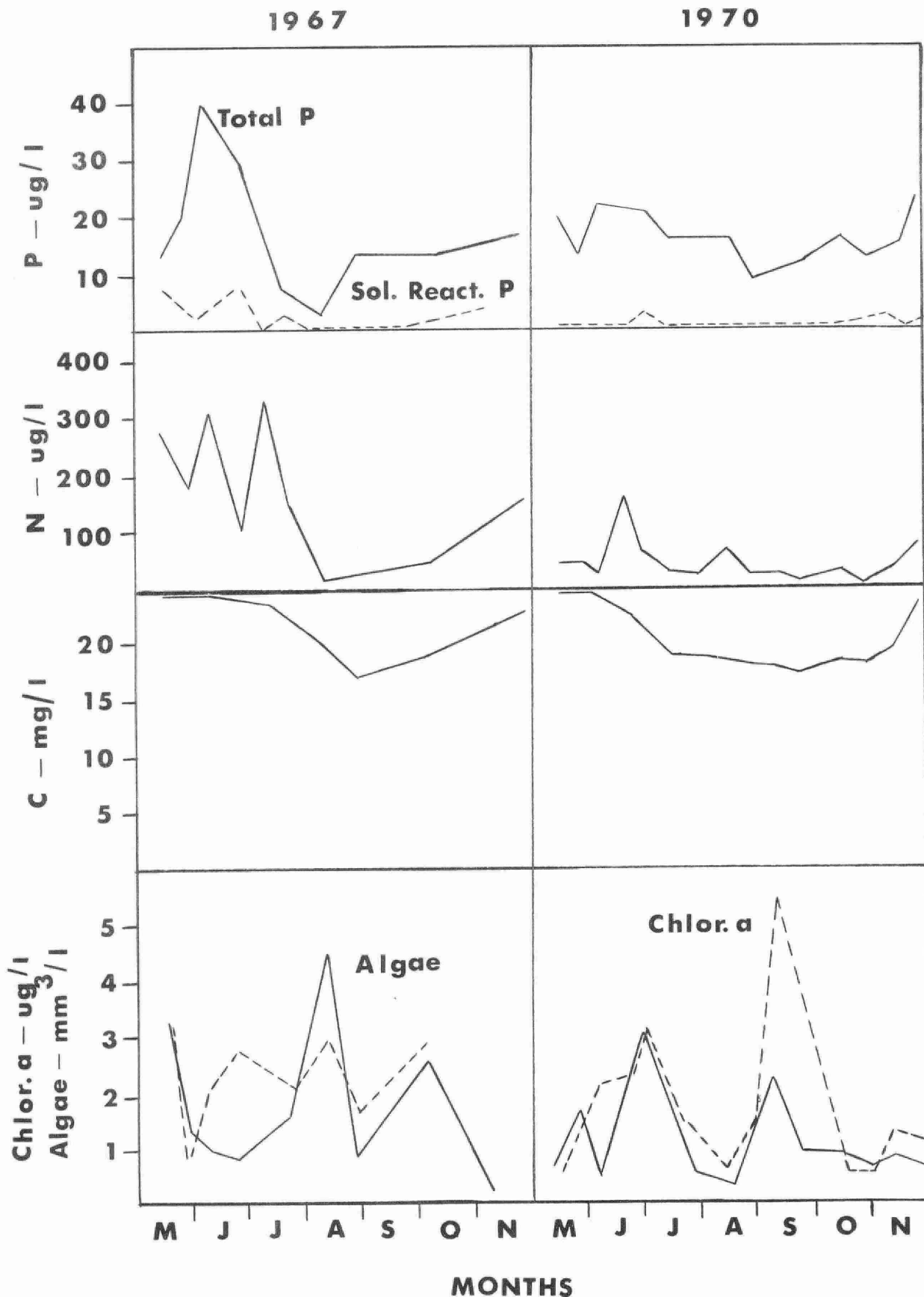


Figure 8

Trophogenic zone variations in 1967 and 1970 of total and soluble reactive phosphorus ($\mu\text{g P/l}$), inorganic nitrogen ($\mu\text{g N/l}$), inorganic carbon (mg C/l), chlorophyll *a* ($\mu\text{g/l}$) and phytoplankton (mm^3/l).

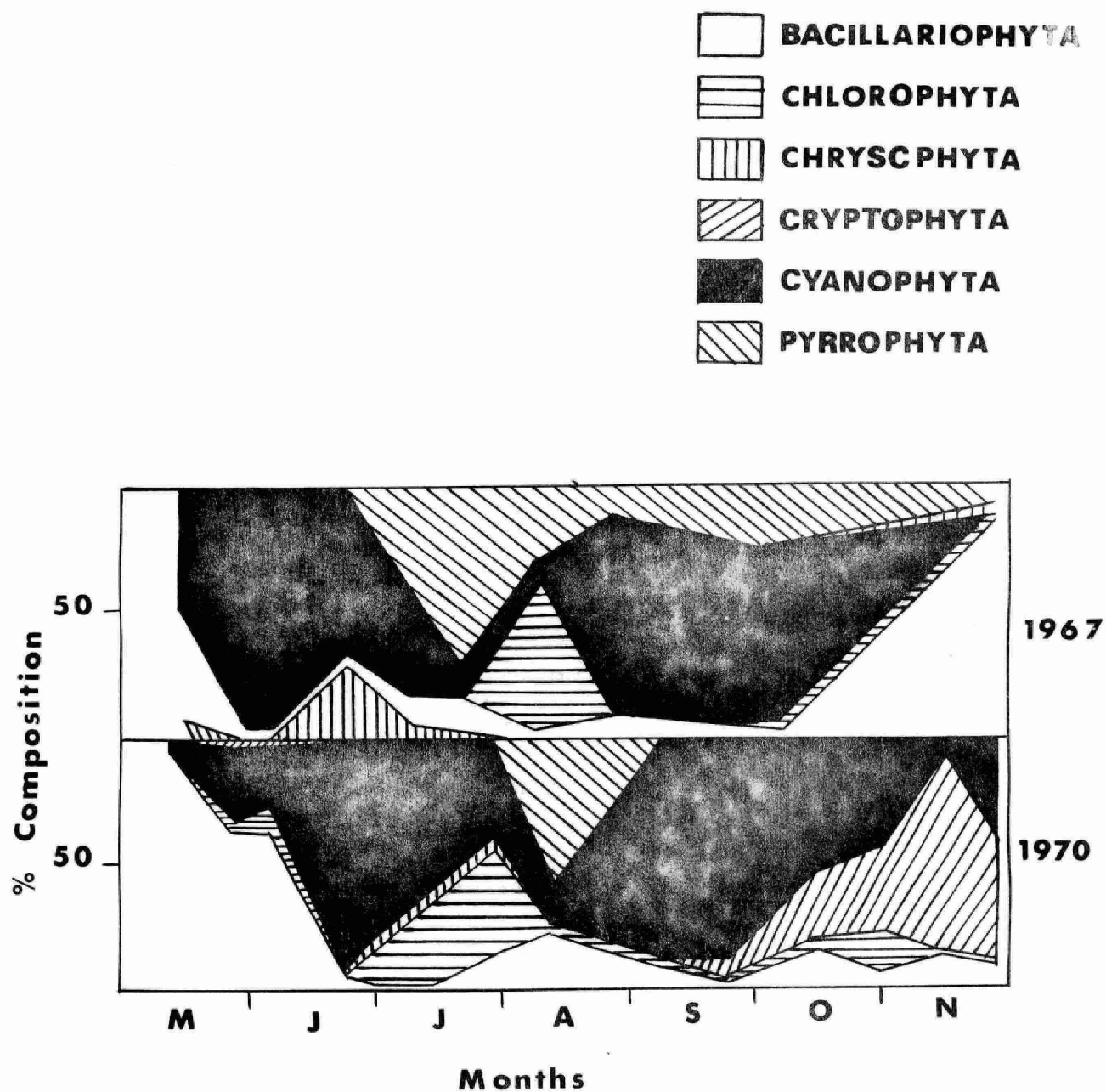


Figure 9

Variations in the percentage composition of the phytoplankton standing crops of the trophogenic zone in 1967 and 1970.

of the community during July. This in turn is followed by a second domination by the Cyanophyta which is subsequently replaced in late autumn by the Bacillariophyta in 1967 and the Cryptophyta in 1970.

Profiles of phytoplankton standing crops in June, August and October, 1967 and at monthly intervals from May to November, 1970 are shown in Figure 10. Large concentrations of Cyanophyta, primarily Oscillatoria spp. are evident at a depth of about 12 metres in May, June, 1970, disappearing by mid-August but reappearing in September. Domination of the community by the Pyrrophyta, consisting mainly of Peridinium spp. and Ceratium spp., is also evident in May and August, 1970. The largest standing crops at any one depth were obtained in May and September, 1970 with concentrations in excess of $6 \text{ mm}^3/\text{l}$. Other phytoplankters encountered during the study are listed in Table III. Chlorophyll a distribution with depth in 1970 (Figure 11) shows a maximum concentration of $17 \text{ } \mu\text{g}/\text{l}$ to have occurred in conjunction with the algal pulse noted at a depth of 12 metres in September. Chlorophyll levels much of the time ranged from less than $1 \text{ } \mu\text{g}/\text{l}$ to about $5 \text{ } \mu\text{g}/\text{l}$.

Carbon fixation associated with the phytoplankton are profiled in Figure 12 and indicate the highest rate of activity to have occurred in May, 1970 ($\text{mg C}/\text{m}^3/\text{hour}$). Dichotomic profiles of photosynthetic

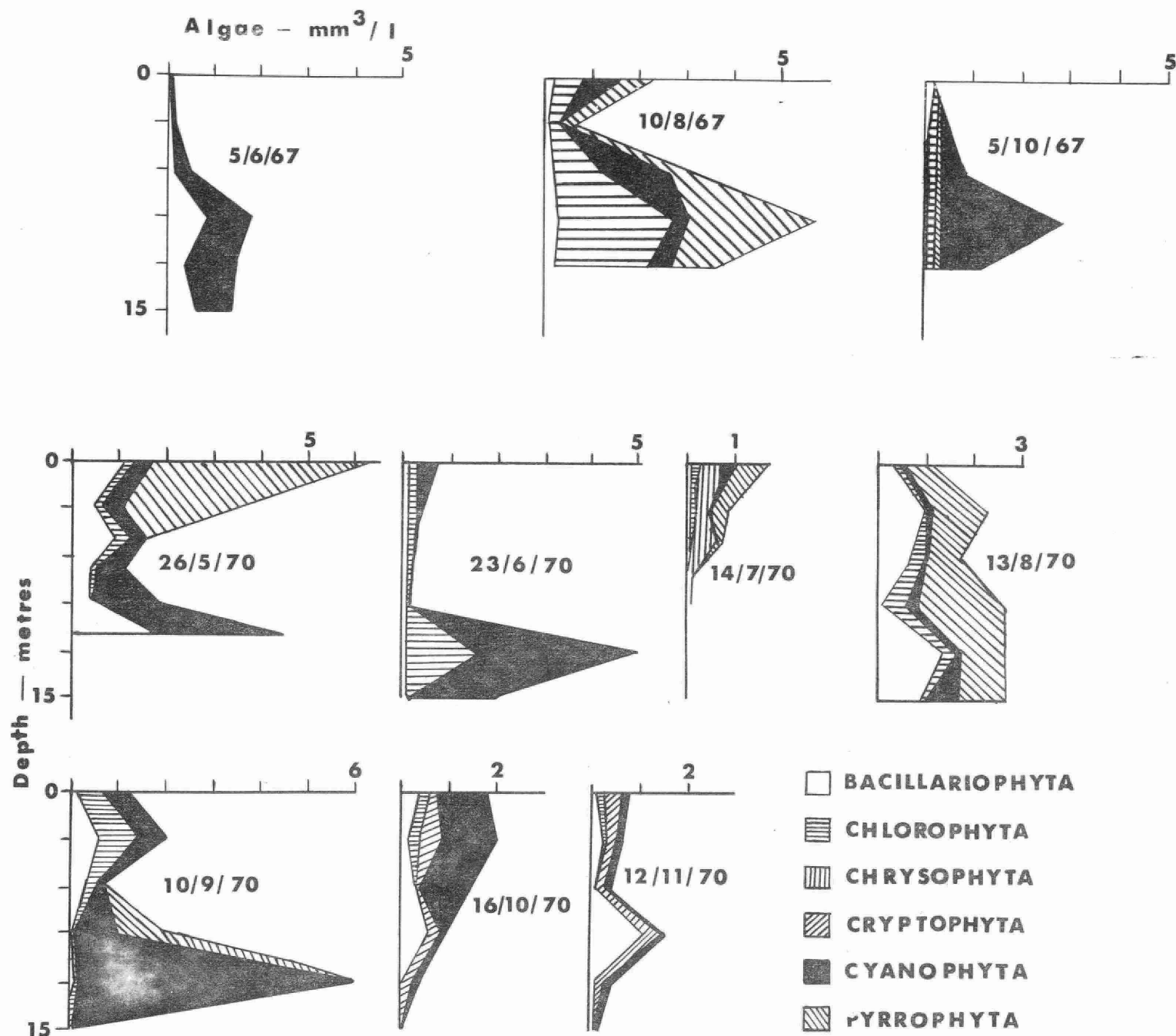


Figure 10
Profiles of the phytoplankton standing crops
observed in 1967 and 1970 (mm³/l).

TABLE III

Phytoplankton of Lake-on-the-Mountain

Bacillariophyta

Amphiprora ornata Baily

Asterionella formosa Hassal

Cocconeis pediculus Ehrenberg

Cyclotella antigua Smith

Cyclotella bodanica Eulenstein

Cyclotella comta Kuetzing

Cyclotella kuetzingiana Thwaites

Cyclotella michiganiana Skvortzow

Cymbella ventricosa Kuetzing

Diatoma spp.

Fragilaria crotonensis Kitton

Gomphonema angustatum Grunow

Navicula spp.

Nitzschia spp.

Pinnularia spp.

Stauroneis spp.

Stephanodiscus astrea Grunow

Stephanodiscus hantzschii Grunow

Synedra acus Kuetzing

Synedra rumpens Kuetzing

Synedra ulna Ehrenberg

Tabellaria fenestrata Kuetzing

continued.....

TABLE III (continued)

Chlorophyta

Ankistrodesmus falcatus Rolf
Botryococcus spp.
Chlamydomonas spp.
Chlorella spp.
Coelastrum microporum Naegeli
Cosmarium spp.
Crucigenia quadrata Morren
Dictyosphaerium pulchellum Wood
Elakatothrix gelatinosa Wille
Francia Droescheri Smith
Lagerheimia spp.
Mougeotia spp.
Oocystis borgei Snow
Oocystis parva West & West
Pediastrum spp.
Quadrigula lacustris (Chodat) Smith
Scenedesmus spp.
Selenastrum gracile Reinsch
Sphaerocystis schroeteri Chodat
Stauroastrum spp.
Tetratum staurogeniaeforme Lemmermann
Tetraedon spp.

Chrysophyta

Dinobryon bavaricum Imhof
Dinobryon cylindricum Imhof

continued.....

TABLE III (continued)

Dinobryon divergens Imhof
Dinobryon sertularia Ehrenberg
Gloeobotrys limneticus Pascher
Synura uvella Ehrenberg
Cryptophyta
Cryptomonas erosa Ehrenberg
Cyanophyta
Anabaena flos-aquae De Brebisson
Anacystis spp.
Aphanizomenon flos-aquae Rolfs
Aphanocapsa spp.
Aphanothece spp.
Chroococcus dispersus Lemmermann
Chroococcus limneticus Lemmermann
Coelasmaerium pallidum Lemmermann
Dactylococcopsis spp.
Gomphosphaeria aponina Kuetzing
Microcystis aeruginosa Kuetzing
Oscillatoria spp.
Euglenophyta
Euglena spp.
Trachelomonas spp.
Pyrrophyta
Ceratum hirundinella Dujardin
Glenodinium borgei Schiller
Peridinium cinctum Ehrenberg

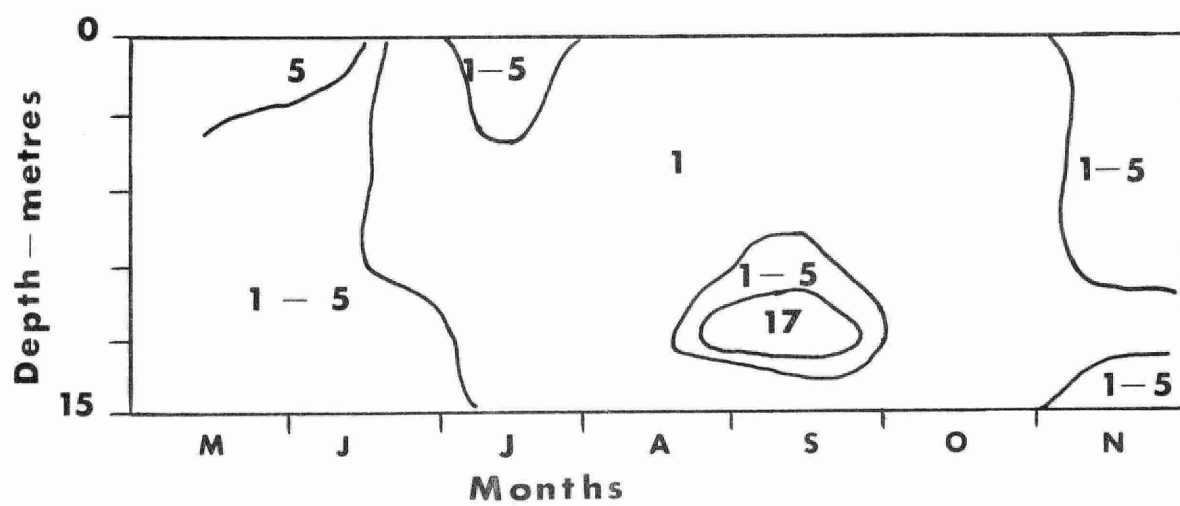


Figure 11

Seasonal depth variations of concentrations of chlorophyll *a* ($\mu\text{g/l}$).

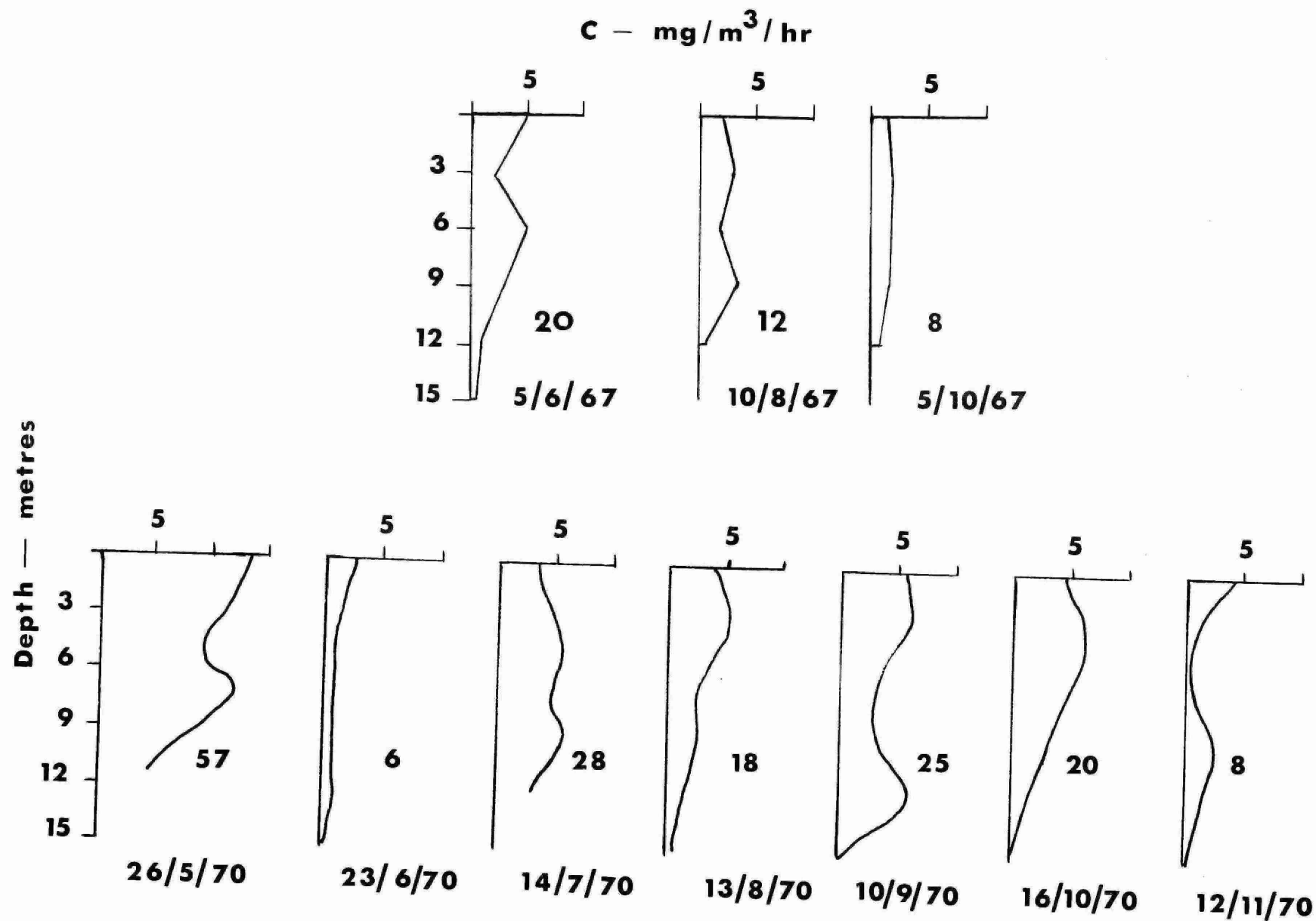


Figure 12

Profiles of phytoplankton photosynthetic activity in 1967 and 1970 per unit volume ($\text{mg C}/\text{m}^3/\text{hour}$) and per unit area ($\text{mg C}/\text{m}^2/\text{hour}$).

activity are evident in both years particularly in May and then later in the summer. Planimetric estimations of the carbon fixation per unit surface area per hour have also been included.

LABORATORY STUDIES

Laboratory Experiment: 1968

From the composite sampling program of 1967 phytoplankton development in the trophogenic zone appeared to be restricted by a limited availability of nitrogen and/or phosphorus. Clarification of this relationship was investigated using samples obtained from a depth of 3 metres from the lake in July, 1968. The results of routine analyses of the lake water are listed in Table IV. Phytoplankton responses in aliquots of raw water enriched with nitrogen and/or phosphorus, after being cultured at the laboratory for a period of two weeks (Figure 13) show that addition of either nutrient alone had no stimulatory effect on phytoplankton development. The percentage composition of the cultures at harvesting (Table V) indicate a decline in the domination by the Cyanophyta of the original sample, being replaced in most samples by the Bacillariophyta and in one case, the highest feeding of nitrogen and phosphorus, by the Chlorophyta.

Laboratory Experiment: 1969, 1970

In vitro experiments to further assess the potential effects of enrichment with nitrogen and phosphorus were carried out using samples of lake water

TABLE IV

Chemistry of Raw Water from Lake-on-the-Mountain
re Laboratory Experiments

		July 1968	August 1969	March 1970
Calcium	mg/l	38	39	46
Magnesium	mg/l	2	3	3
Sodium	mg/l	2	2	2
Potassium	mg/l	1.5	2.0	2.2
Sulphate	mg/l	21	17	18
Chloride	mg/l	3	4	4
Total P	µg/l	10	20	37
Sol. React. P	µg/l	3	5	20
Total Nitrogen	µg/l	403	747	478
Nitrate N	µg/l	20	10	50
Nitrite N	µg/l	3	7	8
Ammonia N	µg/l	80	20	80
Inorganic C	mg/l	19	17	23
Total Iron	mg/l	0.05	0.05	0.05
Diss. SiO ₂	mg/l		1.6	2.2
pH		8.3	8.2	7.7

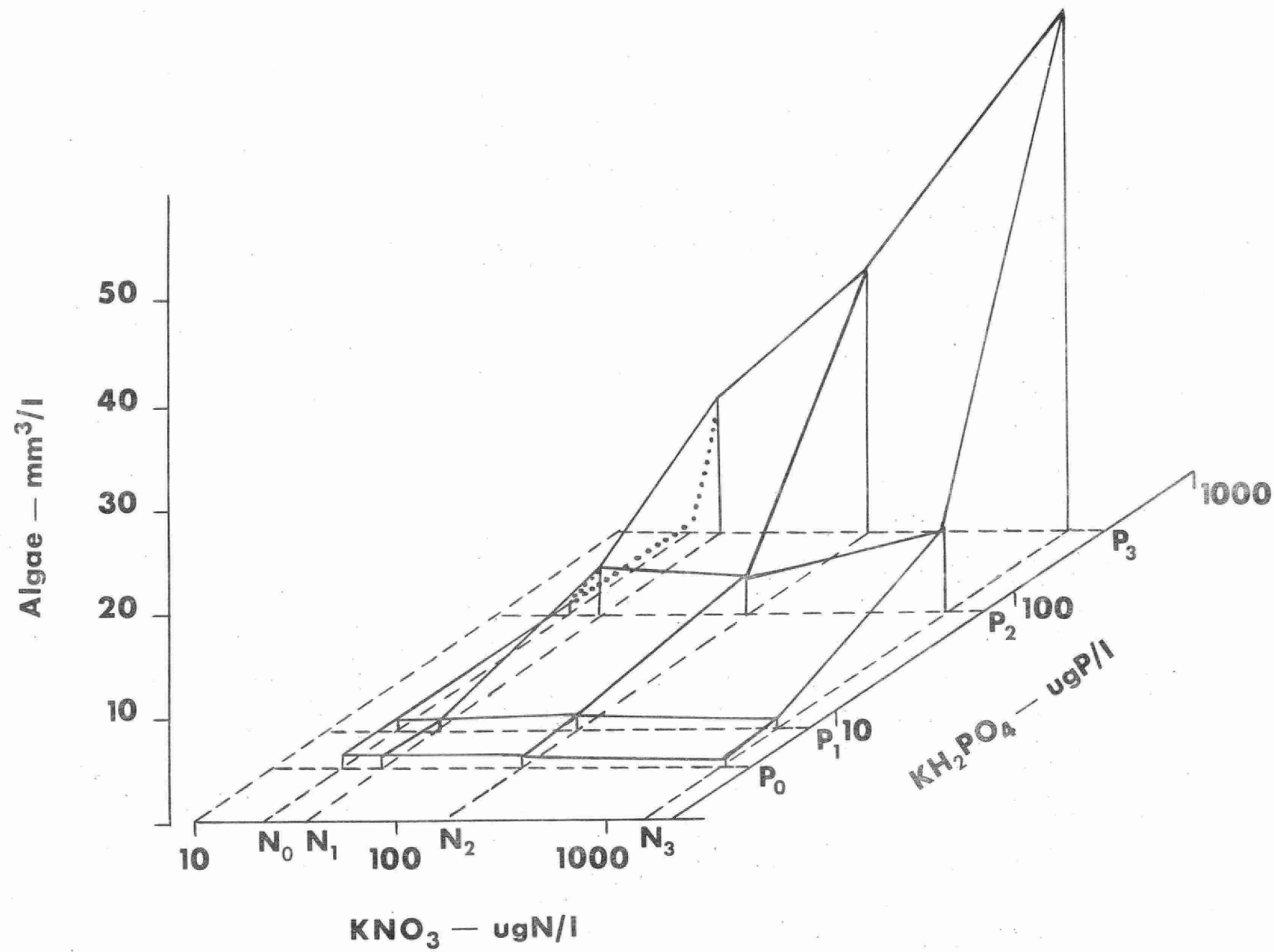


Figure 13

Algal responses (mm³/l) of laboratory raw water cultures after two weeks following enrichment with nitrogen and phosphorus; lake sampled July, 1969.

TABLE V

Percentage Composition of July, 1968 Experiment
initially and when harvested

Initial Raw Water - Bacillariophyta	22
Chlorophyta	15
Cyanophyta	63

After Two Weeks

		P ₀	P ₁	P ₂	P ₃
*N ₀	Bacillariophyta	44	42	33	60
	Chlorophyta	1	-	15	1
	Cyanophyta	55	58	52	39
N ₁	Bacillariophyta	60	38	69	81
	Chlorophyta	1	-	-	-
	Cyanophyta	39	62	31	19
N ₂	Bacillariophyta	62	66	80	72
	Chlorophyta	-	1	-	26
	Cyanophyta	38	33	20	2
N ₃	Bacillariophyta	65	79	90	38
	Chlorophyta	-	-	-	62
	Cyanophyta	35	21	10	-

*N₀P₀ - control system which received no additional
nitrogen or phosphorus

obtained at a depth of 3 metres in August, 1969 and from under the ice-cover in March, 1970. The chemical characteristics of the raw water at these times, presented in Table IV, show the March sample to contain 15 $\mu\text{g/l}$ soluble reactive phosphorus and 100 $\mu\text{g/l}$ inorganic nitrogen more than was present in the August sample.

Graphical presentation of the phytoplankton responses after two weeks of culturing, based on chlorophyll a determinations (Figure 14) have been adjusted to account for the differences between samples with respect to initial soluble reactive phosphorus and inorganic nitrogen concentrations.

Algal responses in both series, after a two week culture period, are very similar at initial soluble reactive phosphorus levels of 60 $\mu\text{g/l}$ or less. No further algal increases at higher phosphorus levels are apparent in the August samples whereas the responses of the March series continue to increase. Ratios between inorganic nitrogen and inorganic phosphorus concentrations in both series up to a phosphorus concentration of 60 $\mu\text{g/l}$ are equal to or greater than 18:1 (wt:wt). Such ratios would suggest that algal development in these cultures may have been restricted because of a low availability of phosphorus compared to nitrogen. Above a phosphorus concentration of 60 $\mu\text{g/l}$ nitrogen to phosphorus ratios are less than 18:1. The difference between the responses of the

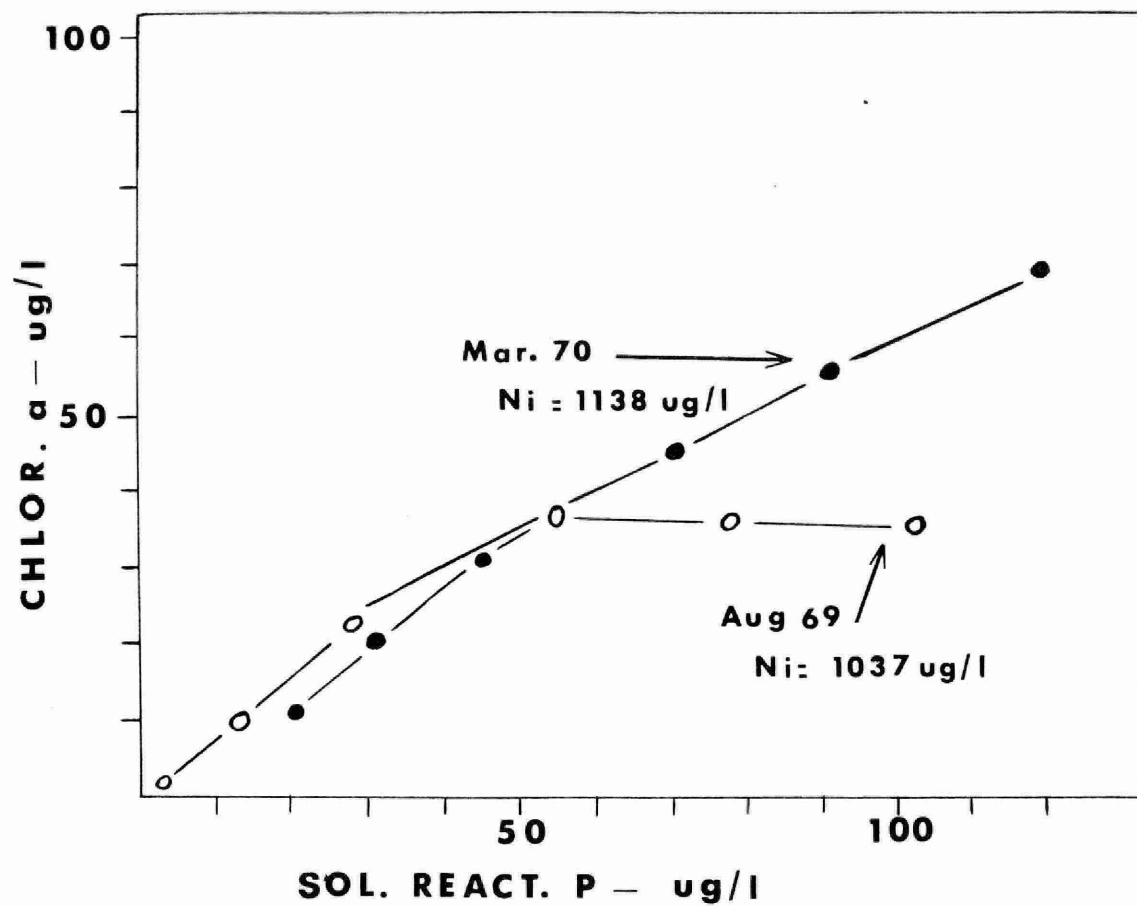


Figure 14

Comparison of algal responses (measured as chlorophyll a - $\mu\text{g/l}$) of laboratory cultures of lake water obtained in August, 1969 and March, 1970, following enrichment with nitrogen and phosphorus after a growing period of 2 weeks.

two series at the higher phosphorus levels is therefore a function of nitrogen availability.

FIELD TRIAL FERTILIZATION EXPERIMENTS

Quantitative and qualitative changes of the phytoplankton communities of the enclosures of the in situ enrichment experiments of Series I, II and III, based on weekly samplings, are portrayed in Figures 15 and 16.

Phytoplankton responses to comparable treatments are lower in Series I than Series II and III. Quantities of algae in all control enclosures declined with time. Addition of glucose, either with or without supplemental feeding of nitrogen and phosphorus was not observed to enhance phytoplankton growth. Addition of nitrogen alone had little stimulatory impact, and development to only phosphorus appeared to maximize by the first week and then decrease. Phytoplankton responses to enrichment with nitrogen plus phosphorus typically reached a maximum level by the third week, the highest concentration of phytoplankton in each series being obtained with the highest loadings of nitrogen and phosphorus. The highest standing crop of phytoplankton occurred with treatment N_2P_2 of Series III - $12.2 \text{ mm}^3/\text{l}$.

The phytoplankton community at the beginning of Series I was dominated by the Cyanophyta, 46 percent, and Chrysophyta, 36 percent, the Chlorophyta and Bacillariophyta making up 16 and 2 percent respectively. The

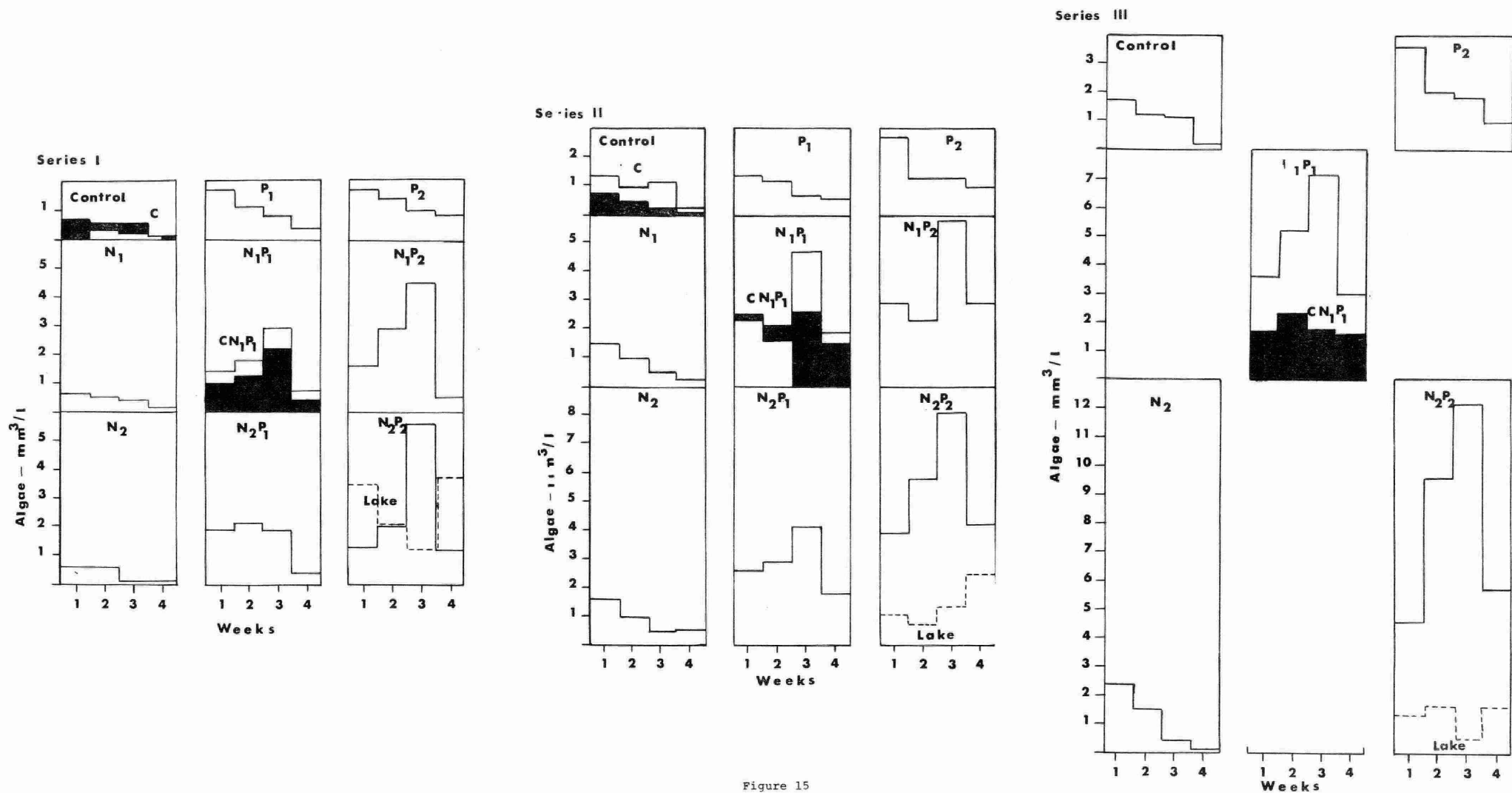


Figure 15

Field trial fertilization experiments - Series I, II, III - weekly changes in phytoplankton quantities (mm^3/l) following enrichment with organic carbon, nitrogen, and/or phosphorus.

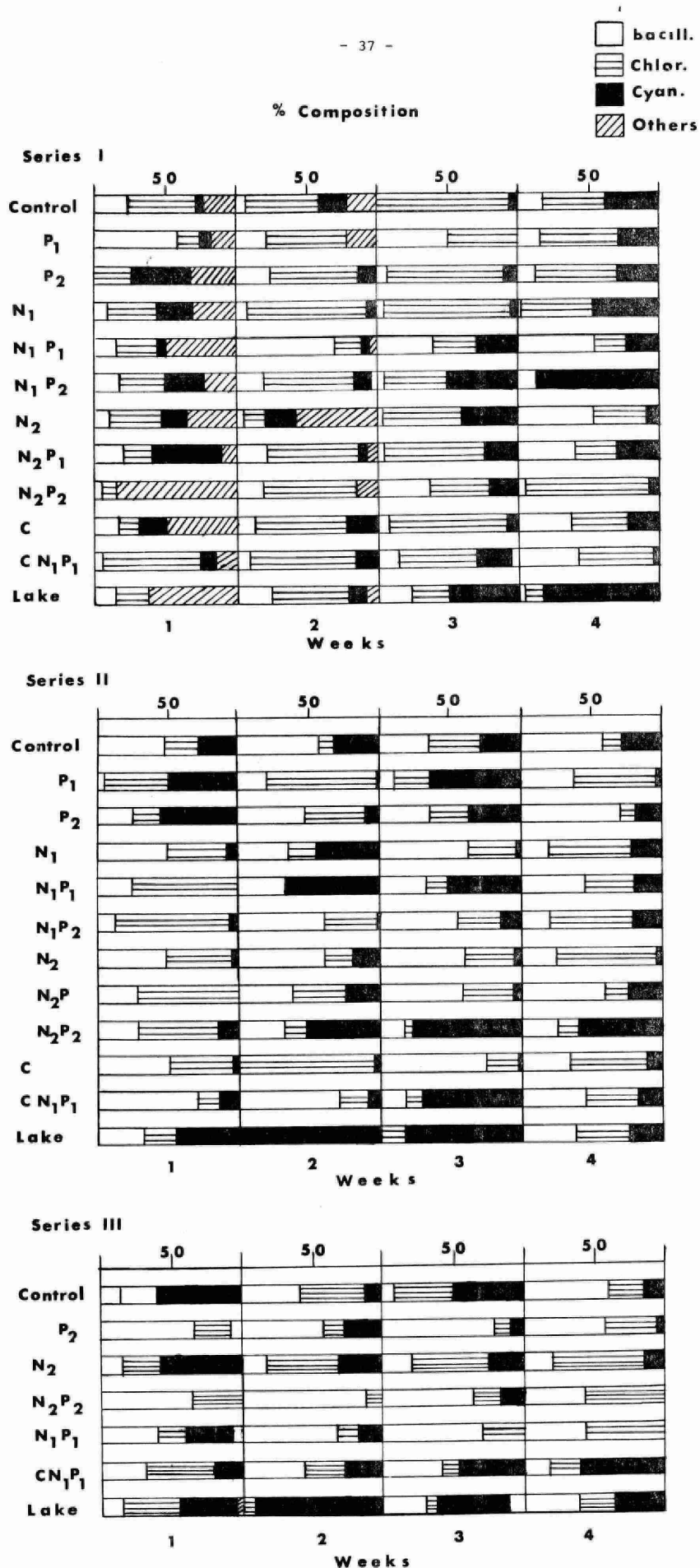


Figure 16

Field trial fertilization experiments - Series I, II, III - weekly variations in the percentage composition of phytoplankton standing crops.

composition of the initial communities of subsequent studies is identical with that associated with the fourth week of the lake sample of the preceding series. The more predominant phytoplankton genera observed in the communities of the various enclosures are listed in Table VI.

Total phytoplankton development associated with the various nutrient regimes of each series, excluding carbon enrichment treatments, was estimated planimetrically from the data of Figure 15 and the resulting values in relation to enrichment with nitrogen and phosphorus, expressed as a per diem loading rate, are illustrated in Figure 17. From examination of the data associated with Series II, which appears to magnify the responses of Series I and is supported by the results of Series III, it is apparent that increasing phosphorus availability without a similar increase in nitrogen supply, or vice versa, did not stimulate phytoplankton development.

TABLE VI

Algal Genera in weekly samples from Series I, II, III
that exceeded 10 percent of total cell volume

	Treatment										C	CN ₁ P ₁
	N ₀			N ₁			N ₂					
	P ₀	P ₁	P ₂	P ₀	P ₁	P ₂	P ₀	P ₁	P ₂			
Bacillariophyta												
Asterionella			X	X								
Cyclotella		X	X	X	X	X	X		X			
Fragilaria	X	X	X	X	X	X	X	X	X	X	X	X
Chlorophyta												
Chlamydomonas	X			X	X		X					X
Coelastrum	X	X	X	X	X	X	X	X				X
Cosmarium	X		X							X		X
Crucigenia	X				X	X		X			X	X
Mougeotia		X			X					X		
Oocystis		X	X		X	X	X			X	X	X
Quadrigula	X						X					
Scenedesmus	X					X		X	X			
Sphaerocystis	X	X	X	X	X	X	X	X	X		X	X
Cyanophyta												
Anabaena	X											
Aphanocapsa	X			X								
Aphanothese	X			X			X	X		X		X
Chroococcus	X	X	X	X	X	X	X	X	X	X	X	X
Coelosphaerium			X		X		X					X
Gomposphaeria			X		X	X					X	
Microcystis	X		X					X				
Oscillatoria		X			X	X		X	X		X	X

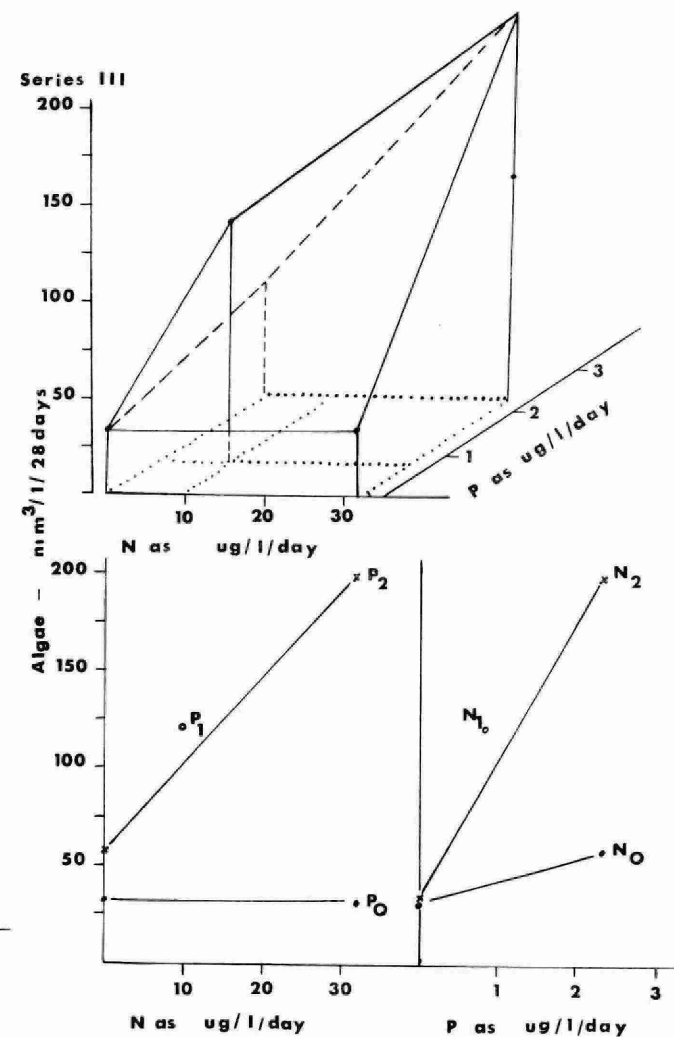
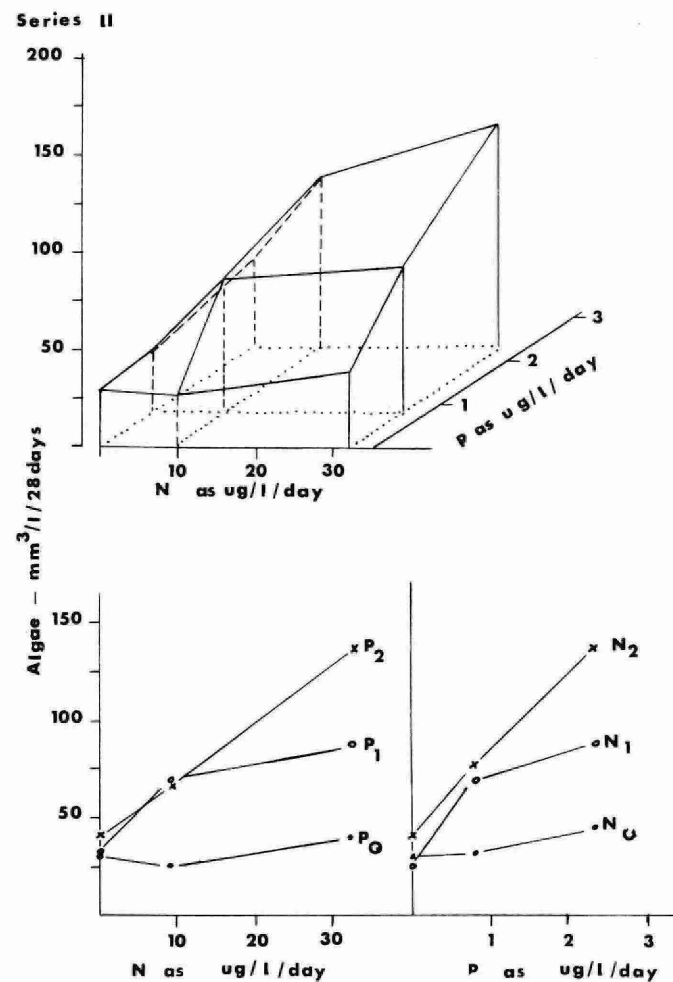
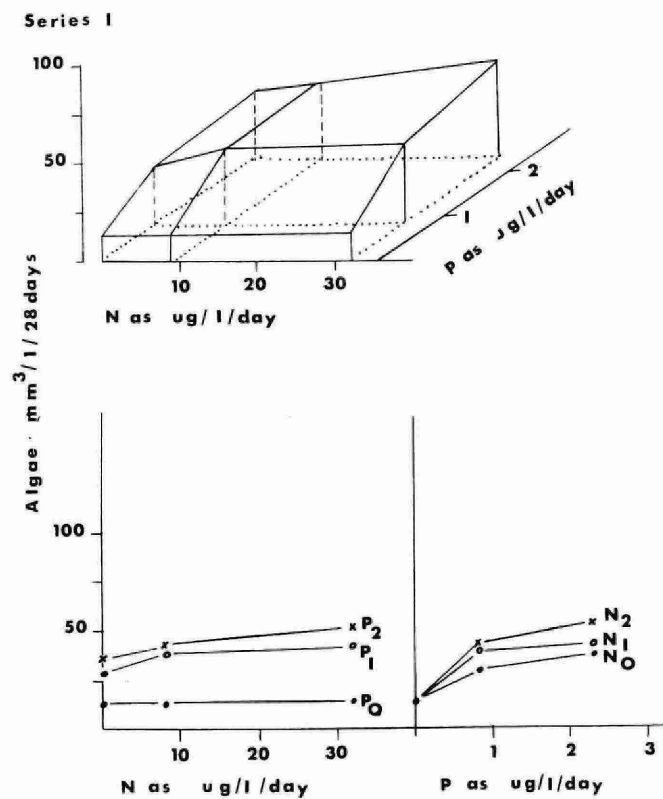


Figure 17

Field trial fertilization experiments - Series I, II, III - total phytoplankton development over the 28 day study period (mm^3/l) in relation to enrichment with nitrogen and/or phosphorus expressed as a per diem loading rate.

DISCUSSION

Lake-on-the-Mountain achieves pronounced thermal stratification by midsummer, the epilimnion and metalimnion penetrating respectively to depths of about 8 and 10 - 12 metres (Figure 3). Oxygen levels which were almost homogeneous with depth in the spring declined within the hypolimnion as the season progressed to concentrations of less than 1 mg/l at depths greater than 15 metres (Figure 4).

From composite sampling of the trophogenic zone phytoplankton levels were never observed to be greater than 5 mm³/l (Figure 8). Mean concentrations of total phosphorus and total nitrogen were 17 µg P/l and 450 - 700 µg N/l (Table II). Alkalinity within the zone declined from slightly above 100 mg/l as CaCO₃ in the spring to about 73 - 88 mg/l (Figure 8).

Distribution patterns of carbon, nitrogen and phosphorus and dissolved silicate (Figures 5, 6 7) indicate that the latter substance became depleted to a level below the suggested critical value of 0.5 mg/l (Lund et al, 1963) only briefly within the metalimnion in August. Epilimnetic inorganic carbon levels decreased considerably with time and a concomitant increase in hypolimnetic concentrations is evident. The highest levels of particulate carbon, nitrogen, and phosphorus were

obtained in conjunction with a pulse of phytoplankton, mostly Oscillatoria, which occurred in late August and early September at the metalimnetic-hypolimnetic interface (Figure 10). Chlorophyll a distribution also maximized at that same location (Figure 11). A zone of supersaturated oxygen at the same depth (Figure 4) would appear to be attributable to the photosynthetic activity of these algae. Carbon assimilation was also found higher at that depth than in the overlying water (Figure 12).

Midsummer carbon assimilation profiles (Figure 12) as well as secchi disc observations (Figure 3) at Lake-on-the-Mountain depict features very similar to those observed by Findenegg (1964) in "Wörthersee which is considered to be an example of mesotrophy. Maximum standing crops of phytoplankton, as based on the composite sampling of the trophogenic zone, lie within a range suggested by Vollenweider (1970) re mesotrophic lakes, $3 - 5 \text{ mm}^3/\text{l}$. Lake-on-the-Mountain would therefore appear to represent an example of a mesotrophic environ.

Maximum algal responses of $50 \text{ mm}^3/\text{l}$ and $40 - 70 \text{ } \mu\text{g}/\text{l}$ chlorophyll a obtained from the laboratory culture experiments (Figures 13, 14) suggest that the epilimnetic waters of Lake-on-the-Mountain both in summer and winter are sufficiently endowed with the various growth factors essential for plant development (Lewin, 1962), other than nitrogen and phosphorus, to support

quantities of phytoplankton far greater than the standing crops of algae observed during either 1967 or 1970.

Synergistic increases in algal biomass to additions of nitrogen plus phosphorus both in laboratory cultures and field enrichment experiments, a result also observed by Christie (1969), Thomas (1969), Polsini et al (1970) and Glooschenko and Alvis (1973), indicate a dual limitation on phytoplankton responses related to the supply of these two nutrients.

The littoral zone of Lake-on-the-Mountain extends to depths greater than 3 metres and supports a luxuriant growth of various macrophytic flora including *Chara* spp., *Potamogeton* spp. and *Ceratophyllum* spp. No attempt was made to either more precisely identify or quantify the density of these beds. The framework supporting the enclosures of the experimental field trials was located within this zone. The columns of Series I, which were designed to enclose a portion of the lake bottom, therefore also encircled a sample of the macrophyte community. The enclosures of Series II, III were bags and did not therefore include this flora. As nutrient enrichment per enclosed volume was equivalent in Series I, II and III, the lower phytoplankton responses obtained from Series I as compared to Series II and III would appear to result from the competition for added nutrients as exerted by the enclosed macrophytic flora.

One might further conclude that the apparent mesotrophic status of Lake-on-the-Mountain as ascertained from mid-lake characterization may in fact reflect the degree to which the macrophyte community removes nitrogen and phosphorus from the epilimnion thus reducing the availability of these nutrients for phytoplankton development. Quantitative phytoplankton changes associated with the bag enclosures of Series II and III, on the other hand, are perhaps more indicative of the type of responses which may be anticipated as a result of nutrient loadings to a moderately fertile environ.

Aside from the early stages of Series I, the phytoplankton populations encountered in these enclosures were made up mainly of Bacillariophyta, Chlorophyta and Cyanophyta, other forms accounting for less than five percent much of the time (Figure 16, Table VI). The absence of any apparent qualitative correlation between community structure of comparable treatments of different studies could be attributed in part to the type of enclosure - column versus bag. The population of the former would include planktonic and tychoplanktonic (forms of the littoral community occurring accidentally in the plankton) algae to varying degrees while the composition of the latter systems are established to a large extent by the community structure of the initial inoculum.

Organic carbon enrichment, in the form of glucose, with or without the addition of nitrogen plus

phosphorus was not found to display any significant stimulatory impact on phytoplankton development and in four out of five tests actually yielded lower maximum responses relative to comparable treatments not receiving glucose (Figure 15). Unlike responses obtained by Christie (1968) and Kerr et al (1970) to carbon enrichment of low alkalinity waters, the above results along with an algal maximum greater than $10 \text{ mm}^3/\text{l}$, following addition of only nitrogen and phosphorus (Figure 15), support the contention of Prince and Bruce (1972) as opposed to the concept of Keuntzel (1969) and observations of Lange (1967, 1970) with samples of Lake Erie water, that excessive growths of phytoplankton in moderately alkaline waters are not restricted due to a limitation in carbon availability.

In field studies, combined additions of nitrogen and phosphorus at the highest level (Figures 15, 17) resulted in maximum and total quantities of phytoplankton to increase between five and seven fold above the control systems, and in one instance produce a level of phytoplankton greater than the suggested breakpoint between eutrophy and hypertrophy - $10 \text{ mm}^3/\text{l}$ (Vollenweider, 1970). Combined additions of these same nutrients at the lower feed rate increased the maximum and total phytoplankton quantities two to four times the controls, the highest maximum rising to above the mesotrophic but within the eutrophic range. Suggested permissible and dangerous annual loading rates of nitrogen and phosphorus to a lake having a mean depth of 10 metres (Vollenweider, 1970) are $1.5 \text{ g N/m}^2 : 0.10 \text{ g P/m}^2$ and $3.0 \text{ g N/m}^2 : 0.20 \text{ g P/m}^2$.

On a per volume per day basis the above are equivalent to about 0.4 $\mu\text{g N/l/day}$: 0.03 $\mu\text{g P/l/day}$ and 0.8 $\mu\text{g N/l/day}$: 0.06 $\mu\text{g P/l/day}$. The lower nitrogen and phosphorus feeding rates of the enclosure studies calculated on a per diem basis are about 8 $\mu\text{g N/l/day}$: 0.9 $\mu\text{g P/l/day}$ and are several fold higher than even the above dangerous loading rates. Therefore, it is not surprising that such enrichment was sufficient to result in a maximum development of phytoplankton to a concentration which is characteristic of a eutrophic environment.

The results of these investigations further imply that nutrient laden inputs (eg. sewage treatment plant effluents) to a receiving water capable of diluting the discharge a thousand fold should be limited to not more than 0.4 mg/l total phosphorus and 6.4 mg/l available nitrogen. The nitrogen value is derived from the ratio between nitrogen and phosphorus associated with phytoplankton requirements of 16:1 (wt:wt). Inasmuch as sewage treatment plant discharges will enter a receiving water all year, whereas algal growth is limited primarily to a six-month period, ideally the concentrations of phosphorus and nitrogen in such discharges should be one-half of the above suggested values to minimize an excessive nutrient build-up during periods of low growth activity.

CONCLUSION

Lake-on-the-Mountain represents a mesotrophic, marl lake which during the summer months develops pronounced thermal stratification and an anaerobic hypolimnion.

Phytoplankton development is restricted due to a low availability of nitrogen and phosphorus, otherwise the lake is quite fertile.

Macrophytic flora of the littoral zone appear to significantly mediate nitrogen and phosphorus availability for epilimnetic phytoplankton development.

Addition of organic carbon as glucose, with or without inclusion of nitrogen and phosphorus, did not stimulate a phytoplankton growth.

Nitrogen and phosphorus enrichment of epilimnetic waters isolated from the macrophytic flora of the littoral zone, at calculated per diem rates of 0.9 $\mu\text{g P/l}$ and 8 $\mu\text{g N/l}$ or greater resulted in maximum phytoplankton concentrations at densities associated with a eutrophic to hypertrophic environ.

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